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Vertical-geometry all-optical switches based on InAs/GaAs quantum dots in a cavity

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Self-assembled InAs/GaAs quantum dots (QDs) incorporated in an asymmetric $GaAs/Al_{0.8}Ga_{0.2}As$ vertical cavity have been employed as an optical nonlinear medium for reflection-type all-optical switches. Switching time down to 23 ps together with wavelength tuning range over 30 nm have been achieved in this structure. An angle-dependent behavior of the switching time has been observed, which suggests there is a coupling mechanism between the ground and excited states in QDs with different sizes. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3180704]

The unique nature of atomlike carrier states in three-dimensional confined quantum dots (QDs) leads to revolutionary characteristics of photonic devices.[1] Attractive properties such as a very-low threshold current density, a high temperature stability and a high modulation frequency have been demonstrated recently for self-assembled InAs/GaAs QD lasers.[2–5] For ultrafast applications, the broad optical spectrum of self-assembled QDs has been employed as an absorption saturator for mode-locked QD lasers and QD semiconductor saturable absorber mirrors.[6,7] Also, QD semiconductor optical amplifiers have achieved ultrafast gain recovery with a time constant of subpicosecond ($<10^{-12}$ s).[8,9] With this impressive early stage performance, it is anticipated that QD devices will constitute indispensable components in the future telecommunication network operating up to 1 Tbit/s.

One of the key devices to establish a high-bit-rate telecommunication network is an optical switch which functions within an ultrashort delay time. As an optical nonlinear medium, self-assembled QDs have been proposed for optical switching with ultralow power consumption in a Mach–Zehnder interferometer.[10,11] However, the low density of QD states requires a very long lateral dimension for the transmission type device and this makes it difficult to integrate within a compact device geometry. For this reason, a vertical structure which can realize low-power, polarization-insensitive, and micrometer-size switching devices is highly desirable. Theoretically, such geometries have been analyzed in terms of the optical Kerr effect inside QDs within a symmetric vertical cavity.[12]

In this work, we have developed a reflection-type structure for ultrafast optical switching which utilizes the nonlinear absorption saturation in self-assembled InAs/GaAs QDs. An all-optical QD switch with an asymmetric $GaAs/Al_{0.8}Ga_{0.2}As$ vertical cavity has been designed, fabricated, and characterized. A switching time down to 23 ps and a wavelength tunability over 30 nm have been achieved in this structure. Our results demonstrate the potential application of QD materials in ultrafast all-optical switching devices.

Figure 1 schematically describes the operation principle of a reflection-type QD switch within an asymmetric Fabry–Pérot (FP) cavity. When a train of optical control pulses excites the front mirror of a FP cavity, the saturated absorption of nonlinear materials (self-assembled InAs QDs in this case) will shift the cavity resonant mode. This yields a fast modulation of the reflection of signal light. To attain a wide wavelength operation window, asymmetric FP cavities with low finesse were incorporated in all-optical switches using quantum well or bulk materials as the optical nonlinear medium.[13,14] However, due to the three-dimensional confined geometry and the broad size distribution, the effective cross section and interaction length for self-assembled QDs are very small to interact with the vertically injected light at certain wavelength. Therefore, a relatively large finesse asymmetric cavity is required to enhance the light-QD interaction. Based on this consideration, InAs/GaAs QDs have been integrated into a vertical cavity which consists of 12 periods of $GaAs/Al_{0.8}Ga_{0.2}As$ for the front mirror and 25 periods for the back mirror. A transfer matrix method (TMM) has been employed to aid the design. Figure 1 shows the calculated spatial distribution of the optical electric field in-

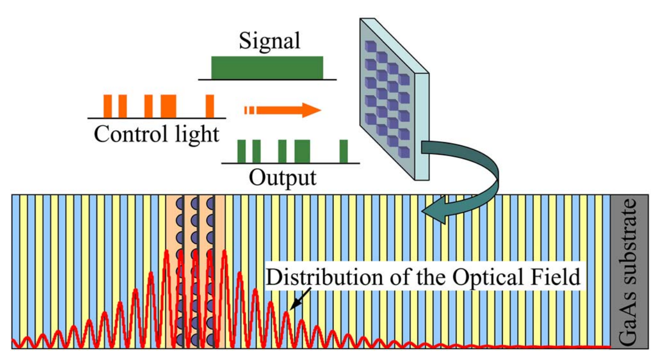

FIG. 1. (Color online) Schematic diagram of an all-optical switch using QDs as an optical nonlinear medium. The vertically aligned FP cavity consists of 12/25 periods of $GaAs/Al_{0.8}Ga_{0.2}As$ for the front/back mirrors. Optical field distribution inside the cavity is shown by the oscillation curve. InAs QD layers are placed at antinode positions of the optical field.

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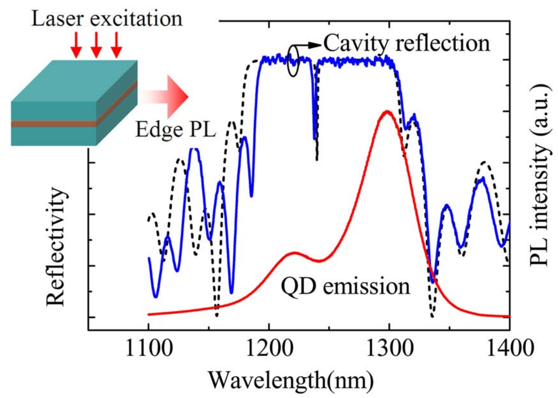

FIG. 2. (Color online) Cavity reflection and PL emission of QDs as functions of wavelength. For cavity reflection spectra, the solid curve presents experimental results while the dashed curve is the theoretical design.

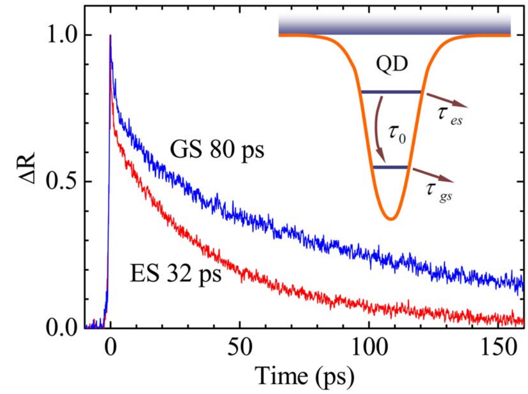

FIG. 3. (Color online) Differential reflectivity as a function of delay time for both switching processes via GS and ES, respectively. The inset shows the carrier dynamics inside a QD.

tensity inside the FP cavity. An optical intensity enhancement of 22 times inside the cavity is obtained from the simulation of this structure.

The wafer was grown on a GaAs (001) substrate by molecular beam epitaxy in an Oxford Instruments V90 system. The InAs QD layers were prepared utilizing the Stranski–Krastanow growth mode by depositing 2.6 ML of InAs within an 8 nm $In_{0.15}Ga_{0.85}As$ quantum well to give a dot-in-a-well (DWELL) structure. Three layers of InAs QDs were placed at antinode positions of the optical field. Cavity reflection spectra from both experiments and calculations, as well as the QD photoluminescence (PL) emission spectrum, are shown in Fig. 2. By measuring edge-emission PL, emission peaks of InAs QDs were observed with the ground state (GS) at 1298 nm and the first excited state (ES) at 1220 nm. The reflection spectrum gives a cavity resonant mode with a finesse value of ~600. The cavity mode wavelength is 1238 μm, which is close to ES. The dashed curve in Fig. 2 indicates a theoretical design by using TMM simulation. It is well matched by the experimental results.

Conventional pump-probe measurements were carried out at room temperature to study the switching dynamics. Orthogonally polarized pump and probe beams were generated by an optical parametric oscillator, which provided 130 fs optical pulses with an 80 MHz repetition rate. With the pump beam exciting the front cavity mirror at the wavelength of cavity resonant mode, the differential reflectivity was measured by the probe signal beam with a power approximately one hundredth of that of the pump power. The pump power was typically set around 10 pJ/pulse with a measured bandwidth of ~20 nm, which is broader than the linewidth of the cavity mode. A switching process with a time constant of 32 ps has been demonstrated, as shown in Fig. 3. The switching curve exhibits an ultrafast component in the initial part of a few picoseconds. This observation is in agreement with another group's reports on QDs.[7,15]

Another wafer has been prepared for comparison with a GS emission peak at 1220 nm and a cavity resonant mode at 1225 nm, obtained by varying the parameters of QD layers and mirrors. This GS switching sample shows a switching time of 80 ps, which presents comparable results with previously reported values for a QD switch using two-dimensional photonic crystal waveguides.[11] The significantly faster response for the ES sample can be explained by the rapid intersubband relaxation of carriers. When an ultrafast optical pulse pumps at the ES, the absorption of the ES becomes saturated. After the pump pulse is removed, a fast relaxation of carriers into the GS recovers the absorption at ES. As a consequence, a faster switching time is suggested and now experimentally demonstrated.

Furthermore, we have investigated the incident angle dependence of the switching performance. Although the cavity mode has determined the operation wavelength for the switch, by changing the incident angle of the optical pulses from 0° to 50°, the operation wavelength can be varied near the ES emission peak from 1240 to 1210 nm. Due to the inhomogeneous broadening of QD spectra, wide wavelength tuning has been achieved. Figure 4 shows the cavity mode wavelength as a function of the incident angle, which was experimentally measured (solid triangles) and calculated using the TMM simulation (dashed curve). The angle-dependent switching time (open circles) decreases with decreasing wavelength and a minimum switching time of 23 ps is reached using this configuration at the ES emission wavelength. For wavelengths shorter than 1220 nm, the switching time keeps constant. Therefore the present QD switch using ES has been shown to operate over a wavelength range of 30 nm with a 23–32 ps switching time.

Only processes with a time constant faster than the minimum switching time could be mainly responsible for the wavelength dependent behavior. Accordingly, a photon coupling process[16] due to the overlap between the absorption spectra of the QD ES and GS is employed to explain the

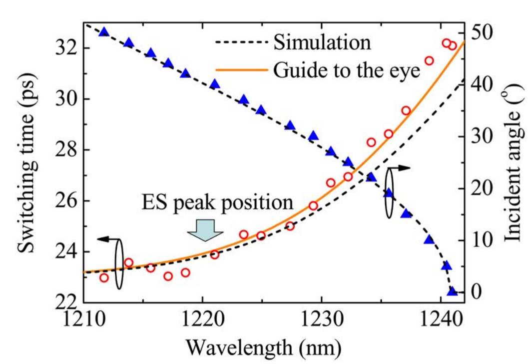

FIG. 4. (Color online) Wavelength dependence of the switching time (open circles). By changing the incident angle, the operation wavelength of the QD switch is tuned from 1210 to 1240 nm (solid triangles). Dashed curves are from simulation results.

wavelength-dependent switching time. For 1.3 μm QDs with a DWELL structure, a bimodal distribution of QDs has been always observed in our previous work.[17] The second subset of QDs presents an optical transition partially overlapped by the ES transition peak. Hence, the optical absorption of the pump light near the ES emission peak is always from different-size QDs with ES and GS transitions. Assuming the absorption intensities of the GS and ES are A_1 and A_2, respectively, the absorption changes as function of time can be described by a summation of two exponential decays:

$$\Delta\alpha(t) = A_1 \exp\left(-\frac{t}{\tau_{GS}}\right) + A_2 \exp\left(-\frac{t}{\tau_{ES}}\right). \quad (1)$$

In the case of $A_2 \gg A_1$, by using the second term expansion of the Taylor series,

$$\Delta\alpha(t) \approx (A_1 + A_2)\exp\left(-\frac{t}{\tau_1}\right), \quad (2)$$

where

$$\tau_1 = \left(\frac{A_2}{A_1 + A_2}\tau_0^{-1} + \tau_{GS}^{-1}\right)^{-1} \quad (3)$$

is the observed angle-dependent switching time, with $\tau_0 = (1/\tau_{ES} - 1/\tau_{GS})^{-1}$. In the simulation, we have assumed that the second distribution in the bimode has a GS peak at 1260 nm. The carrier decay times of the GS and ES are 80 and 23 ps as measured. This simulation reproduces very similar behavior to the wavelength-dependent switching time in Fig. 4. The deviation in the longer wavelength region is caused by the increasing violation of the inequality: $A_2 \gg A_1$ when the operating wavelength approaches that of the bimodal GS peak.

It is interesting to attach a physical meaning to the time constant τ_0 in the above equation. If we assume that the total carrier escape rate via thermalization[15] and recombination is almost the same for both the GS and ES, the only difference between the carrier decay times of GS and ES is the intersubband carrier relaxation. The parameter τ_0 therefore is indicative of the intersubband relaxation time. By this simple means, an intersubband carrier relaxation time of ~32 ps can be estimated in our QDs. It should be noted that carriers remaining in GS may influence the relation between the delay times and induce a deviation from the relationship among the carrier life times. This could result in slower decay via the ES. Therefore, a faster sweep out of remaining carriers from the GS (e.g., by controllably introducing a nonradiative recombination channel) could be an effective approach to reduce the switching time for both the GS and ES cases, and therefore enable faster operation of these QD switches.

In summary, we have developed a vertical-geometry all-optical switch device based on self-assembled InAs QDs within a $GaAs/Al_{0.8}Ga_{0.2}As$ vertical cavity structure. Pump-probe measurements have shown a switching time of 80 ps via QD GS and 23 ps via QD ES, confirming that the fast intersubband transition of carriers inside QDs is an effective means to speed up the switching process. These results indicate that the proposed structure involving QD materials is potentially suitable for compact all-optical switches for future ultrafast telecommunication systems.

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